Date: June 21, 2019

EIC Detector R&D Progress Report

Project ID: eRD18
Project Name: Precision Central Silicon Tracking & Vertexing for the EIC
Period Reported: January 1 to June 21, 2019
Project Leader: Peter G. Jones
Contact Person: Peter G. Jones

Project Members:
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Abstract

We propose to develop a detailed concept for a central silicon pixel detector for an Electron-Ion Collider at BNL or JLab exploring the advantages of depleted MAPS (DMAPS) to achieve improved spatial resolution and timing capability over traditional MAPS. The sensor development will exploit the Birmingham Instrumentation Laboratory for Particle Physics and Applications. An accompanying simulation study will optimise the basic layout, location and sensor/pixel dimensions to find the best achievable momentum resolution and vertex reconstruction resolution. This initial design study will allow future full-detector simulations to explore precision measurements of heavy flavour processes and scattered electrons at high Q^2.

1. Report

1.1 What was planned for this period?

The project is divided into two work packages. WP1 focuses on sensor development and WP2 focuses on detector layout simulations. For this period, the plan for WP1 was to fully characterise the modified TJ 180 nm CMOS process, by testing all three TJ investigator chips with radioactive sources and with eTCT measurements. At the same time, we planned to work with chip designers at RAL to carry out a feasibility study of pixel design and readout architectures, and further refine specifications for an EIC DMAPS sensor. For WP2, we aimed to study momentum resolution and impact parameter resolution as a function of pseudorapidity and by varying the position of the first and second disks.

In addition, we received several recommendations from the Committee following our January presentation. These are listed below, pointing to the sections of the report where the recommendations have been followed up:

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- Reconcile the differences in resolution between the various simulation tools and between eRD16 and eRD18. (Partially completed – please refer to section 1.2.3.)
- Further advance and clarify the characterization studies underway for the TJ structures. (Completed – please refer to section 1.2.1.)
- Clarify with eRD16 the role and necessity of a timing layer, particularly since you propose to expend EIC R&D resources on electronic design for it. It would be great to see a more definitive and coherent discussion of this in July. (Please refer to section 1.2.2.)
- Carry out the proposed design plan, which has been funded, at RAL. (Ongoing – please refer to section 1.2.2.)
- Pursue with eRD16 a broader tracking workshop. (We have discussed this with eRD16 and we propose to organise a tracking workshop as a satellite meeting to the POETIC Conference to be held at the Lawrence Berkeley Laboratory between 16-21 September. We hope to have more to report at the meeting in July.)

1.2 What was achieved?

In this section, we divide our report into two sections corresponding to the work packages defined above.

1.2.1 WP1 – TJ technology investigations

During the past six months, the TJ technology investigations focused on understanding results of the TJ1b investigator. With respect to the first investigator chip (TJ1, which we reported on in January 2018), this version of the chip allows the p-well containing the electronics and the substrate of the sensor to be biased separately, in order to create a larger depletion volume and a higher electric field. This feature was added with the aim of improving charge collection with respect to the first investigator where the sensor bias voltage was limited to -6 V.

Tests have been carried out on a 28 x 28 μm^2 pixel using a ^{55}Fe source. This pixel was tested in the previous version of the investigator and showed the best performance in terms of charge collection. The aim of these tests was to assess the improvement with higher bias voltage. Preliminary results were presented in January, which were not in agreement with expectations. Since then more biasing configurations have been carried out with higher statistics in order to understand the results. The new measurements are shown in Fig. 1, which compares the the measured rise time distribution for different biasing configurations (-6 V, -9 V, -12 V and -15 V) and the rise time as a function of signal amplitude with a sensor bias voltage of -15 V. These measurements show that by increasing the sensor bias voltage, the rise time distribution shifts to the left and becomes broader tending toward a bimodal distribution. The pulses with slowest rise times are correlated with the smallest amplitudes.

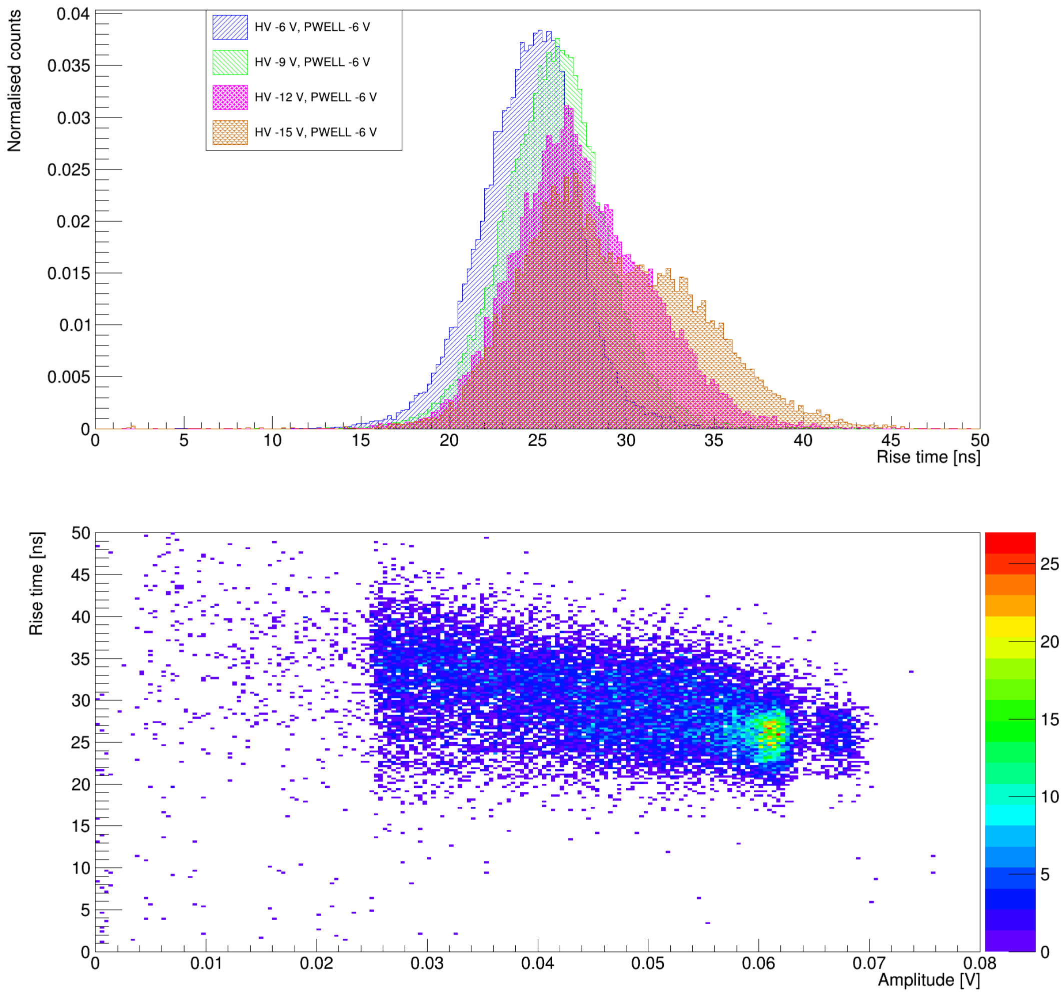


Figure 1. Rise time (top) and rise time versus amplitude (bottom) measured on a 28 x 28 μm^2 pixel of the TJ1b chip using a ^{55}Fe source. In the bottom plot the sensor bias voltage is -15V.

This behaviour was not observed in the 20 x 20 μm^2 pixel as shown in the rise time distributions in Fig. 2. Investigations on larger pixel sizes were not carried out as these have larger spacing between the charge collection electrode and the p-well that is known from measurement of the TJ1 to lead to slower and less uniform charge collection in the modified process.

Similar results have been obtained by collaborators testing MALTA [1] and TJ-MONOPIX [2] DMAPS sensors from the same submission as the TJ1b. These are fully monolithic sensors, with zero suppressed readout and 25 ns time resolution. Whilst the sensor design is common with the two prototypes, MALTA features an asynchronous readout architecture, and TJ-MONOPIX a column-drain readout architecture. These devices have been characterised in test beams before and after irradiation and were found to have a low tracking efficiency after irradiation, in particular at the edges of the pixels [1, 2].

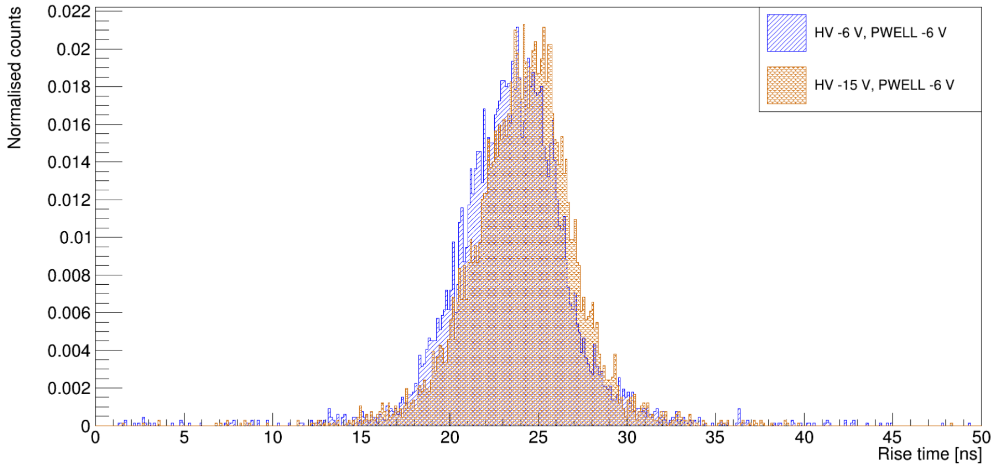


Figure 2. Rise time distributions measured on a 20 x 20 μm^2 pixel of the TJ1b chip using a ^{55}Fe source comparing bias voltages of -6 V and -15 V.

From TCAD simulations, these results are now understood to originate from the sensor design[†]. These simulations were carried out by colleagues at CERN who have obtained the necessary technological information from TJ [3]. Simulations of the MALTA pixel layout showed an issue with the electric field configuration at the edge of the pixel. Charges collected in this region are pushed into a potential minimum between pixels and then slowly drift to the collection electrode. Increasing the sensor substrate voltage leads to even slower charge collection and reduced signal from the edges of the pixel. TCAD results, together from those from the MALTA sensor, highlighted that this issue is related to the extent of the p-well containing the electronics.

These findings agree with our observations on the TJ1b. In a 28 x 28 μm^2 pixel, the rise time distribution widens, and small charges from the pixel edge appear as a second slower peak for increasing HV. For smaller pixel sizes, where the p-well covers a smaller percentage of the pixel size, the charge collection speed is not influenced by the HV.

Two technological solutions have been proposed to improve the charge collection properties of the TJ 180 nm modified process. One consists of having a gap in the deep n-well implant between pixels, and the other of adding an extra deep p-well in the area between the pixels [1, 3]. Simulations have shown that both solutions bend the electric field lines towards the collection electrode leading to faster charge collection and larger signal from pixel edge. With these improvements, increasing the HV does not degrade charge collection.

These improvements, together with improvements in the readout design, have been implemented in the Mini-MALTA sensor [1]. This sensor implements various sectors, to compare the performance of the original MALTA design and the modified sensor

[†] In the case of the MALTA and TJ-MONOPIX there were also some features specific to the design of the readout of these sensors.

layout with the n-well gap and the extra deep p-well implant. We are currently analysing test beam results of the Mini-MALTA in collaboration with colleagues from CERN and Oxford. The test beam was performed at the Diamond facility at the Rutherford Appleton Laboratory with a focused 8 keV X-ray beam. Preliminary results show improved tracking efficiency, demonstrating that more uniform in-pixel charge collection can be achieved with the proposed process modifications. Tests with HV above the p-well bias voltage show that the improved charge collection properties are maintained. Results from these tests cannot be shown here as they are being prepared for publication.

Following these recent developments, we have compiled a summary of all the results we have obtained with the TJ investigator chips, that we attach as a separate file to this report (see appendix 2). Given the necessary modifications to the technology, these chips are no longer representative of the latest process implementation, and technology investigations will continue with more recent prototypes (see section 2.2). From the investigations carried out so far on the TJ chips and the mini-MALTA, we conclude that the modified process improves charge collection, but sensor layout is crucial. In particular, the spacing between the collection electrode and the p-well should be in the order of a few micrometres, and an n-gap or deep p-well is needed in between the pixels. Increasing the substrate bias voltage can improve charge collection, but only with the modifications in the inter-pixel region. Without the n-gap or extra deep p-well, the technology performance appears to have a *sweet spot* for 28 x 28 μm^2 pixels, with few micrometres electrode spacing, biased with a common -6V on the p-well and the substrate.

1.2.2 WP1 – EIC-specific sensor development

Work with the chip designers at RAL started in May (see 1.5) and an updated schedule is attached in appendix 1. Monthly meetings are organised between us and RAL to discuss progress and to decide upon the next steps. This work aims to complete a feasibility study into a dedicated EIC-DMAPS sensor matching the requirements specified in the "EIC Detector Requirements and R&D handbook" [4]. With respect to ALPIDE, improvements in the integration time, power consumption and material budget would be beneficial, together with the capability to time stamp the bunch crossings where the primary interaction occurred.

The Committee asked us to clarify the role and necessity of a timing layer capable of timestamping individual bunch crossings. The answer to this question partly depends on the filling scheme of the EIC machine. Taking RHIC as an example, in polarised proton-proton collisions the two beams are filled with alternating bunch polarisations. One beam is filled with alternate bunches having opposite spin directions/helicities (e.g. +, -, +, -, +, -, +, -, …) while the other beam is filled with alternate pairs of bunches having opposite spin directions/helicities (e.g. +, +, -, -, +, +, -, -, …). This means that successive bunch crossings sample the four possible spin combinations (i.e. ++, -+, +- and --), which helps to control systematics. Spin observables typically require the different spin combinations to be separated, hence it is important to record which bunch crossing corresponds to each event. In a worst-case scenario, a timing resolution of the order of 1 ns would be required at the EIC.

In principle, any fast detector likely to be hit in any event could be used to associate the event with the corresponding bunch crossing and hence determine the spin combination of colliding bunches. Our proposal seeks to determine whether a silicon timing layer could provide the required time resolution without degrading the overall tracking and vertexing performance of the detector. Our simulation studies have already shown that a relatively thick outer layer of 1.6% X/X_0 (twice the radiation length of the ALICE ITS outer barrel layers) does not adversely affect the transverse momentum resolution or pointing resolution in the inner barrel region combining the silicon tracker and a TPC. The aim of the feasibility study is to find the smallest pixel size that will meet the timing and power density specifications that we have imposed.

We have now completed a literature review that included ALPIDE, MALTA, TJ-/LF-MONOPIX, MuPix, and published information on the modified TJ 180 nm process. Specifications have been further updated and are presented in Table 1. Two sets of specifications are presented, one for the vertex and tracking detector without timing capability, and one for a timing layer with capability to tag bunch crossings. The latter could require larger pixel sizes and higher power consumption and would thus be implemented as a timing layer at larger radii, to avoid degrading vertex and tracking measurement, which demands the smallest practical pixel size and very low material. In the interest of setting a demanding specification, we will first attempt to design a sensor that meets the requirements of both cases simultaneously, and as the study progresses, evaluate whether descope options are needed (i.e. relaxing the power requirements or designing two different sensors). With respect to the table presented in January, we have defined maximum pixel size for an outer timing layer to match the TPC resolution, power, noise and fake hit rate figures based on the ALPIDE specifications that should be maintained or improved by an EIC DMAPS sensors. Important figures that are still missing are particle rate, global and local occupancy. Whilst results from our eRD16 collaborators show that tracks occupancy is expected to be very low, experience from HERA shows that beam background could be an issue. We are hoping to be able to provide these figures based on the findings of eRD21 “EIC Background Studies and the Impact on the IR and Detector”.

We are now starting to look into the pixel design, focusing on methods to achieve the required time resolution. Preliminary schematics simulations are starting based on the ALPIDE front-end design to investigate time walk correction methods. In particular we have started to look at constant fraction discrimination, and TOA/TOT calibration as used in the TimePix ASIC.

Table 1: Updated specifications for an EIC DMAPS detector. Two sets of specifications are collected, one for the vertex and tracking detector without timing capability, and one for a timing layer with capability to tag bunch crossings.

	EIC DMAPS Sensor	
Detector	Vertex and Tracking	Timing Layer
Technology	TJ or similar	
Substrate Resistivity [kohm cm]	1	
Collection Electrode	small	
Detector Capacitance [fF]	<5	
Chip size [cm x cm]	Full reticule	
Pixel size [µm x µm]	20 x 20	max 350 x 350
Integration Time [ns]	2000	2000
Timing Resolution [ns]	N/A	< 9 (eRHIC) < 1 (JLEIC)
Particle Rate [kHz/mm2]	**TBD**	
Readout Architecture	Asynchronous	**TBD**
Power [mW/cm2]	< 35	
NIEL [1MeV neq/cm2]	10^{10}	
TID [Mrad]	< 10	
Noise [electrons]	< 50	
Fake Hit Rate [hits/s]	$< 10^{-5}$/evt/pix	
Interface Requirements	**TBD**	

1.2.3 WP2 – Detector layout simulations

Over the last period, most of our effort has gone into the technology investigations described in section 1.2.1. The Committee asked us and eRD16 to do more work to understand the differences observed in the simulations presented in our December report. The differences are illustrated in Fig. 3, which shows the relative momentum resolution of electrons at pseudorapidty $\eta = 3$ for various pixel sizes.

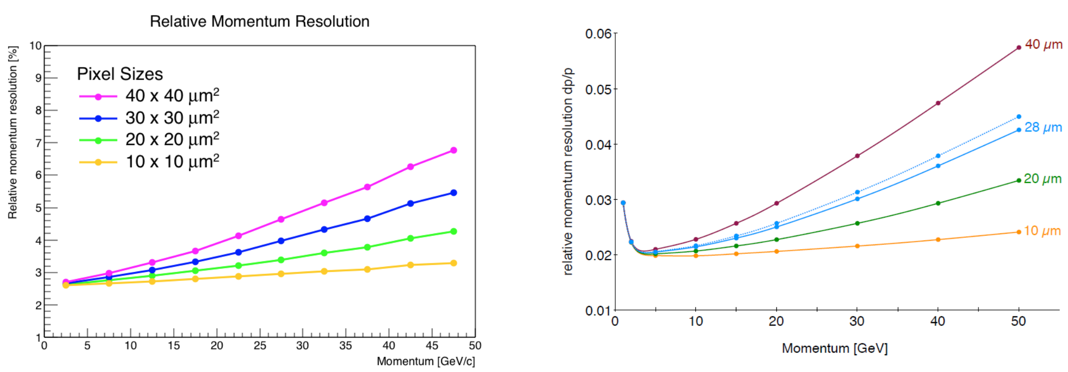


Figure 3. The relative momentum resolution of electrons at pseudorapidity $\eta = 3$ for various pixel sizes. The left panel shows results from an EicRoot simulation (this work). The right panel shows results from eRD16 using the LDT framework. Both simulations incorporate a beryllium beampipe of thickness 0.8 mm.

The Committee noted that there are two notable differences: the upturn at momenta below 5 GeV/c, seen in the LDT framework of eRD16 but not in EicRoot, and the systematically higher values reported by us. The discrepancy at low momentum is being investigated by eRD16. The systematic effect is now understood to be due to differences in the fit range used in the relative momentum distributions. These distributions have significant tails. In Fig. 4, we show a comparison of the relative momentum resolution using a narrower fit interval, corresponding to ± 1.4 sigma of the central peak, comparable to the fit range used by eRD16. The results for the narrower fit range are a better measure of the central peak and agree more closely with the results of eRD16.

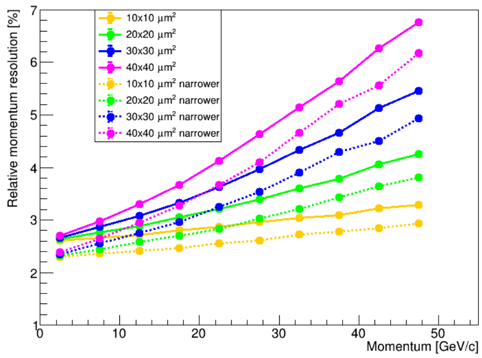


Figure 4. The relative momentum resolution of electrons at pseudorapidity η = 3 for various pixel sizes comparing wide and narrow fit intervals. The results were obtained using the EicRoot simulation and incorporate a beryllium beampipe of thickness 0.8 mm.

1.3 What was not achieved, why not, and what will be done to correct?

The feasibility study into a specific EIC DMAPS sensor was due to be well advanced at this stage and the final report should have been submitted to the panel in July. Due to administrative delays, this work started four months later than planned. The work is now proceeding according to the planned schedule and will be completed by the end of the year.

1.4 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The answer to this question is covered in the Proposal section below.

1.5 What are the critical issues

The modified 180 nm TJ process is certainly suitable for this project given the low capacitance design that can be achieved together with full depletion and charge collection by drift. It is clear from the results obtained with our tests and by collaborators working on this technology, that more development work is needed to fully exploit the potential benefits of the planar deep n-implant. As this technology has not been selected by ATLAS for the HL-LHC upgrade, the source of the necessary funding for further developments is unclear at the moment. One more round of submissions is planned for this year with prototypes to become available in Q1 2020 (see section 2.2) from the ATLAS-ITk pixel groups. Given the promising developments and large interest around this technology, groups are working on finding alternative funding options and applications of this technology.

2. Proposal

2.1 Introduction

Our proposal for the next funding period (FY20) builds upon our original proposal and remains focused on the design of a precision central silicon tracking and vertex detector for a future EIC detector. The relevance for the EIC is high precision tracking and the identification of secondary vertices in the central region. As such, the requirements for the detector are driven by the reconstruction of displaced vertices from the decay of charmed and beauty hadrons. The focus of the EIC physics programme on the role of gluons in the structure of hadrons places a strong emphasis on heavy flavour observables. Heavy flavour production is directly sensitive to the gluon density in the hadron beam at lowest order as well as probing a wide range of issues in perturbative QCD. Similarly, the use of heavy flavours as probes of deconfinement in relativistic heavy-ion collisions provides further motivation to study the same observables in e+A collisions, where cold nuclear matter effects can be explored. Open charm production in polarised e+p scattering has also provided insight into the role of gluons in determining the spin structure of the proton. These points are fully recognised in the EIC White Paper [5] but there is no detailed study to date which looks closely at the optimization of the central silicon tracker layout to address this physics.

2.2 Proposed programme of work

The proposed programme of work for the next year is to bring this initial R&D phase to a close, and to prepare for future work that would lead to a prototype DMAPS sensor meeting the EIC specifications. In discussion with eRD16, we believe that the basic layout simulations are now complete and we have baseline performance plots for both the central and forward regions. We are currently preparing a joint report summarising the status of the layout simulations. In the next year, we will turn our attention to the reconstruction of charm decays.

2.2.1 WP1 – TJ technology investigations

The technology investigation will need to continue to assess the readiness of the TJ modified process, that has been identified as the technology of choice for this project (see July 2018 report). New versions of the MALTA and TJ-MONOPIX DMAPS prototypes will be available in Q1 2020 with the necessary technology modifications to prevent the issues encountered in previous submissions. These will be tested in the lab, and possibly in test beams.

2.2.2 WP1 – EIC-specific sensor development

The feasibility study will be completed by end of 2019 and a final report will be submitted to the panel with the project report in January 2020. The results of this study and of the technology investigations will inform the next steps in order to reach the design and production of a first EIC DMAPS sensor. A plan towards this aim will be presented in July 2020.

2.2.3 WP2 – Detector layout simulations

The detector simulations carried out within the scope of WP2 and in collaboration with eRD16 will be summarised in a report over summer. Starting from these initial layout studies, full-detector simulations will start to explore precision measurements of heavy flavour processes at high Q^2. As highlighted in previous reports, preliminary investigations of e-p collisions at $\sqrt{s}$ = 31.6, 63.2 and 141.4 GeV using Pythia have shown that charm mesons are produced over a typically wide range in pseudorapidity. This is illustrated in Fig. 5 below, which shows the D^0 pseudorapidity distribution at $\sqrt{s}$ = 141.4 GeV (20 GeV x 250 GeV). The full radial coverage of the central tracker (VST+TPC) is shown by the blue shaded region. The red shaded region shows where there is partial coverage by the outer tracker (TPC) where the placement of the first forward/backward disks may enable charm reconstruction, albeit with lower resolution due to shorter track lengths. We therefore propose studying the placement of the innermost forward/backward disks within the outer silicon barrel layers.

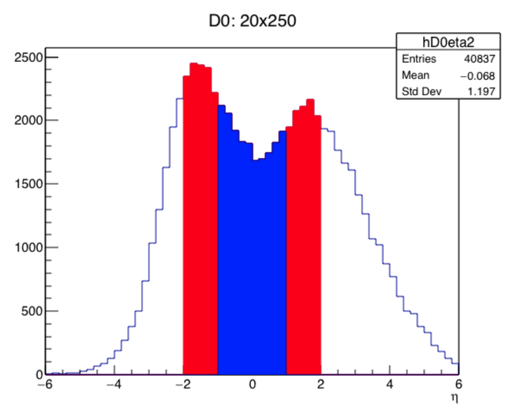


Figure 5. The pseudorapidity distribution of D^0 mesons in e-p collisions at $\sqrt{s}$ = 141.4 GeV. The electrons are travelling in the negative pseudorapidity direction. The shading corresponds to the full (blue) and partial (red) coverage of the outer tracker.

3. Request for resources

Wherever possible existing resources will be devoted to the project. This includes academic time (see Personnel), computing resources and consumables. The University of Birmingham provides funds to support a 3.5-year Ph.D. studentship, which was taken up by Håkan Wennlöf in October 2017. The work proposed to continue the technology investigation and to perform full-detector simulations will be carried out using these resources. The EIC-specific sensor feasibility study will be completed with funding awarded in FY19, which has been committed but not yet spent.

In order to participate in the tests of the new TJ and LFoundry DMAPS prototypes we need to purchase new readout boards ($4k). In addition, we request support for travel ($14k) to enable participation in EIC meetings and visits to collaborators. The total request for FY20 is therefore $18k. The lower requested level of funding in FY20 reflects the on-going work needed to complete the work planned for FY19.

Table 2: FY20 cost breakdown for the three funding scenarios.

Scenario	Equipment	Travel	Total (USD)
100%	$4,000	$14,000	$18,000
80%	$4,000	$10,000	$14,000
60%	$4,000	$7,000	$11,000

4. Personnel

Include a list of the existing personnel and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located and who supervised their work.

Prof. Peter Jones (0.05 FTE) – no cost
Dr. Laura Gonella (0.1 FTE) – no cost
Håkan Wennlöf – (1 FTE) – no cost
Prof. Phil Allport and Prof. Paul Newman have an advisory role and participate in our regular project meetings to monitor progress.

5. External funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

The University of Birmingham provides the Ph.D. studentship that supports Håkan Wennlöf. In addition, our bid to support some of the R&D elements of this proposal through EU Horizon 2020 has been successful. This formed part of the NextDIS work package included in the STRONG-2020 proposal. The proposal has been awarded €62.5k to support the submission of an EIC DMAPS sensor prototype.

6. Publications

Please provide a list of publications coming out of the R&D effort.

None at this stage of the project.

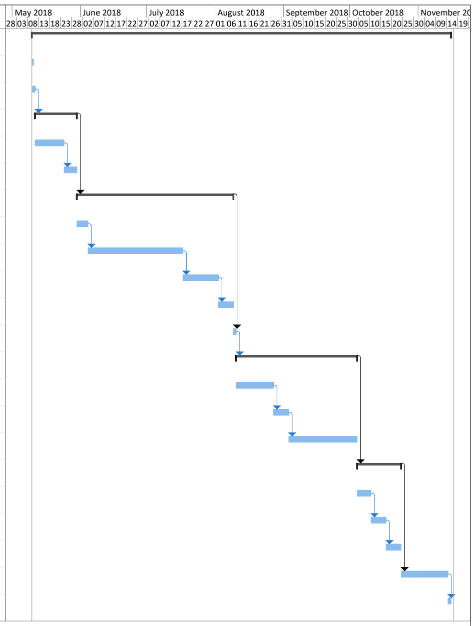
7. References

[1] R. Cardella *et al, MALTA: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade,* 2019 *JINST* **14** C06019
[2] I. Caicedo *et al, The Monopix chips: depleted monolithic active pixel sensors with a column-drain read-out architecture for the ATLAS Inner Tracker upgrade,* 2019 *JINST* **14** C06006

[3] M. Munker *et al, Simulations of CMOS pixel sensors with a small collection electrode, improved for a faster charge collection and increased radiation tolerance,* 2019 *JINST* **14** C05013
[4] "EIC Detector Requirements and R&D handbook", http://www.eicug.org/web/sites/default/files/EIC_HANDBOOK_v1.1.pdf
[5] A. Accardi et al., (EIC White Paper), Electron Ion Collider: The Next QCD Frontier, Understanding the glue that binds us all, Eur. Phys. J. A (2016) 52:268.

Appendix 1

ID	Task Mode	Task Name	Work	Duration	Start	Finish	Predecessors
1		**Project**	**96.67 days**	**147 days**	**Thu 10/05/1**	**Fri 16/11/18**	
2		Spend to Date	1 day	1 day	Thu 10/05/18	Thu 10/05/18	
3		PDR	1.33 days	1.33 days	Thu 10/05/18	Fri 11/05/18	
4		**Literature Review**	**14 days**	**14 days**	**Fri 11/05/18**	**Wed 30/05/1**	**3**
5		Literature Search and Study - Pixel Design	10 days	2 wks	Fri 11/05/18	Thu 24/05/18	
6		Summarise existing technologies and solutions	4 days	0.8 wks	Thu 24/05/18	Wed 30/05/1	5
7		**Pixel Design**	**34.33 days**	**55 days**	**Wed 30/05/1**	**Thu 09/08/1**	**4**
8		Selection of Architecture(s) for simulations	3.33 days	3.33 days	Wed 30/05/1	Mon 04/06/1	
9		Schematic Design and Simulation	20 days	6.67 wks	Mon 04/06/1	Tue 17/07/18	8
10		Simulation of alternative architectures	8 days	2.67 wks	Tue 17/07/18	Thu 02/08/18	9
11		Basic Layout Proposal	3 days	5 days	Thu 02/08/18	Thu 09/08/18	10
12		IDR1	1 day	1.67 days	Thu 09/08/18	Fri 10/08/18	7
13		**Readout Design**	**25 days**	**41.67 days**	**Fri 10/08/18**	**Thu 04/10/1**	**12**
14		Literature Search and Study - Readout Design	7 days	11.67 days	Fri 10/08/18	Mon 27/08/1	
15		Architecture Selection	3 days	5 days	Mon 27/08/1	Mon 03/09/1	14
16		Design and Simulation	15 days	5 wks	Mon 03/09/1	Thu 04/10/18	15
17		**Global Effects**	**9 days**	**15 days**	**Thu 04/10/1**	**Wed 24/10/1**	**13**
18		Calibration	3 days	1 wk	Thu 04/10/18	Wed 10/10/1	
19		Power distribution	3 days	5 days	Wed 10/10/1	Wed 17/10/1	18
20		Interfacing	3 days	5 days	Wed 17/10/1	Wed 24/10/1	19
21		Report Writing	10 days	3.33 wks	Wed 24/10/1	Wed 14/11/1	17
22		FDR	1 day	1.67 days	Wed 14/11/1	Fri 16/11/18	21



Project: ExampleProjectPlan
Date: Wed 19/06/19

Task · Split · Milestone · Summary · Project Summary · External Tasks · External Milestone · Inactive Task · Inactive Milestone · Inactive Summary · Manual Task · Duration-only · Manual Summary Rollup · Manual Summary · Start-only · Finish-only · Deadline · Progress · Manual Progress · Manual Progress

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Figure A1: Workplan for the feasibility study of an EIC DMAPS sensor

Appendix 2

See the attached file – eRD18-TJ-Summary-Jun19.pdf